*The second Joseph W. Richards Memorial Lecture, delivered at the Sixty-fourth General Meeting of The Electrochemical Society, held at Chicago, Ill., September 8, 1933.*

# FARADAY AND HIS ELECTROCHEMICAL RESEARCHES.[1]

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## INTRODUCTION.

It is a particularly happy thought that the Electrochemical Society should honour the memory of Faraday at its meeting which is held in conjunction with the Century of Progress International Exposition at Chicago, for it was exactly 100 years ago that Faraday carried out his major electrochemical researches.

By these researches the science of electrochemistry was first given a firm foundation. To Faraday also the electrochemical industries are deeply indebted both for this work and for his fundamental discoveries in electromagnetic induction which initiated all our modern methods for generating electric current.

## FARADAY THE MAN.

The story of Faraday's life makes most fascinating reading and even today deserves study by all who wish to follow a science career.

Faraday was born in 1791 at Newington Butts, London. His father was a blacksmith. He himself started working as a newsboy and then became apprenticed to a bookbinder, the opportunities of which occupation he used to great advantage in his self-education. It was whilst so employed that one of the firm's clients gave him the opportunity of attending some lectures by Sir Humphrey Davy at the Royal Institution. His record of these lectures, neatly written out and bound by himself secured him the appointment in March, 1813, as assistant in the laboratory at the Royal Institution at 25 shillings ($6) a week. After six months work at the Royal Institution, not having previously been more than 12 miles away from his home, he started on a European tour as private assistant to Sir Humphrey Davy, which lasted 18 months. Such a tour must have differed greatly from similar journeys at the present

[1] Second Joseph W. Richards Memorial Lecture, Century of Progress International Exposition, Chicago, Ill., September 8, 1933. A Lecture in commemoration of the hundredth anniversary of the discovery of the two basic laws of Faraday.

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day. Firstly, England and France were at war, but despite this, after temporary difficulties on landing, Davy and his party secured a most friendly reception by French scientists and even by Napoleon. Secondly, the slow progress of the journey gave opportunities for real scientific work to be carried out in the private laboratories of eminent scientific men in the different countries visited. The experience which Faraday gained and the educational effect upon him of this journey must have been very great.

When they returned to England in April, 1815, Faraday was reappointed at the Royal Institution and, despite many tempting offers, remained there throughout his life.

The Royal Institution, founded in 1800 by Benjamin Thompson (Count Rumford), an American, with the somewhat curious object of bringing scientific lecturers before gatherings of Society for the benefit of the poor, had a great struggle for its existence in early days; and Faraday's loyalty did much to prevent its collapse. From 1815 until 1821 Faraday was Lecture Assistant to the Professors of the Royal Institution, helping Sir Humphrey Davy with his work, and carrying out independent researches, mostly of a chemical nature. In 1821 his position was changed to that of Superintendent of the House and Laboratory and in 1826 he started the "Christmas Lectures to a Juvenile Audience" and the Friday Evening discourses which have been continued ever since and hold such world-wide repute. Up to 1833 when Mr. John Fuller founded the first "Fullerian" Professorship, with life tenure for Faraday, his remuneration did not exceed $500 per annum. From 1829 to 1849 Faraday also gave lectures at the Royal Military Academy, Woolwich, for which he was paid and up till 1831 he was earning a relatively large income by "professional business"—consulting work, etc. In that year he deliberately threw over all such work, and the income which it yielded, in order to concentrate on his electrical researches which had then reached their really important stage. For the rest of his life, at great self-sacrifice, he devoted himself wholly to pure scientific work. John Tyndall, who was Professor of Natural Philosophy at the Royal Institution from 1853 to 1887, writing 65 years ago, says "Taking the duration of his life into account, this son of a blacksmith, and apprentice to a bookbinder, had to decide between a fortune of £150,000 ($750,000) on the one side and his undowered science on the other. He chose the latter, and died a poor man. But his was the glory of holding aloft among the nations the scientific name of England for a period of forty years." It might be

interesting to try to estimate the benefit the world has gained by Faraday's unselfish scientific work!

Other facets of Faraday's character are shown in some of the quotations given in an Appendix to this lecture; and those who have not yet done so are recommended to read at least one of the biographies quoted and particularly to look into the Laboratory Note Books or "Diary" which is now being reproduced verbatim with its numerous sketches by Faraday of the apparatus he used. For a recent appreciation of Faraday's electrochemical researches and their relation to the subsequent developments of electrochemical theory, reference should be made to Sir Harold Hartley's address to the British Association in 1931.

### THE WORLD ONE HUNDRED YEARS AGO.

Before we can really appreciate the majesty of Faraday's work, we must try and prepare our minds by a consideration of the world's condition a century ago. The extraordinary advance in the available material resources of civilisation is difficult to realise without an effort.

There is only space for one or two illustrations. In 1833 the "Royal William," built in Canada, the first steam packet to cross the Atlantic, took 17 days. Up to that time the Post Office allowed an average of 9 weeks for sailing packets to and from Halifax, N. S., and England.

The total world's production of metals 100 years ago, in the peak year 1929 and in 1932 is given in the following table. These data will help to bring home the meagre resources available at that period.

*Approximate World's Production in Short Tons.*

| | 1833 | 1929 | 1932 |
|---|---|---|---|
| Copper | 32,000 | 2,127,000 | 960,000 |
| Lead | 100,000 | 1,931,000 | 1,270,000 |
| Zinc | 14,000 | 1,620,000 | 875,000 |
| Tin | 13,000 | 214,000 | 112,000 |
| Aluminum | nil. | 310,000 | 224,000 |

Laboratories at that time were very different from those we know at present. They were mostly aptly described as "kitchens." Prof. W. T. Brande, of the Royal Institution, in his Manual of Chemistry published in 1819, gives an illustration of the laboratory showing its primitive equipment, including a plant for the distillation of coal to supply the gas; and Faraday in his "Chemical Manipulation," published in 1827, whilst providing the world with a manual of technique, the

result mainly of his own manipulative training and skill, exposes the difficulties of scientific research at that period by indicating a limitation of resources which would daunt the courage of many present day workers, e.g., friction matches were not available.[3] Liebig's Laboratory at Giessen, reputed to be the first teaching laboratory for chemistry, although started in 1824, was only equipped in 1834.

## PRE-FARADAY ELECTROCHEMISTRY.

In 1789 Paets Van Troostwijk and Deimann first decomposed water into hydrogen and oxygen by electrical discharge, but as late as 1797 G. Pearson shows that 14,600 discharges were required to produce ⅓ cubic inch of gas. The great work of Allesandro Volta and Aloysii Galvani from 1782 to 1800, not only gave us access to methods for the production of electricity by chemical processes, but by providing simple apparatus encouraged a vast number of experimenters to work in this field. From the year 1800 a rapid accumulation of new knowledge was achieved. Apart from the amateur experimenters, one section of serious workers from Ermann to Ohm studied the laws of the flow of current, whilst another from Nicholson and Carlisle to Davy and Faraday sought the source of the current in the voltaic pile and found it in the chemical reactions which were occuring. The polemics of the contact versus the chemical theory of the galvanic pile lasted however for a very long period.[4]

From the earliest days of the last century data were also rapidly collected on the decomposition of chemical substances by the electric current. Isolation of the alkali metals by Sir Humphrey Davy in 1807 proved the climax of these electrolytic investigations and naturally created a great impression upon chemical science.

Volta's "Potential Series" of the metals publicly announced to the Paris Academy of Sciences, before Bonaparte, in 1801; the conception of Grothuss of the mechanism of electrolytic conduction and the electrochemical theories of Berzelius and Davy all helped to explain the chemical and electrical phenomena. But, as we shall see, Faraday, rejecting all metaphysical theories and insisting on relying on rigid experimental proofs, carried our knowledge far forward by the few years of painstaking work which he devoted to his electrochemical researches.

[3] Of some historical interest is the description in this book of a laboratory non-luminous gas burner which antedates the Bunsen burner (1866) by some 40 years.

[4] See review of this subject by Oliver Lodge. Brit. Association Report 1884, p. 464-529.

## FARADAY'S METHOD OF WORK

Above all, Faraday was an experimentalist; but he combined with great manipulative skill, an unusual habit of methodically recording the notes of his observations and a fertile imagination duly controlled by experiment and by skillful judgment.

His method of work is now clearly exposed in the reproduction of his laboratory note books or Diary, the publication of which is in progress. Day by day he noted down the experiments performed and the ideas upon them which were passing through his mind. His bibliographical references show that he kept in touch with other cognate work in England and abroad. Despite his high capacity for visualising the fundamental principles of the phenomena he was studying, Faraday was never happy unless he could subject his ideas to experiment and demonstration. He even records that the work of others was never quite clear to him unless he could repeat it with his own hands.

Faraday never used formal mathematics and, in consequence, somewhat mystified his mathematical contemporaries, but both Clerk Maxwell and Helmholtz, who in later years did so much to bring Faraday's work to fuller fruition, record that undoubtedly he possessed a mathematical mind and carried through such of his work as required it on strictly correct mathematical principles, however different from the traditional methods of the time they may have been.

Another marked intellectual capacity which helped Faraday greatly in his work was the rare gift of being able mentally to picture space relationships, as for instance in his "lines and tubes of force" so often brought into use in his electromagnetic researches. Faraday's genius for finding the correct solution through the maze of mysteries he was investigating has rightly given him a foremost place amongst scientific investigators. As Kohlrausch said of him "Er riecht die Wahrheit" (He scents the truth) in all that he studied.

On the point of note making, Faraday from his earliest days worked most methodically, and again and again he stresses the value of collecting notes and observations and above all keeping them in a properly numbered and dated form. His electrical researches are entered in his laboratory notebook, each page dated, and the 16,041 paragraphs numbered in series and sequence. Even his published papers are conveniently arranged in numbered paragraphs, the Electrical Researches comprising 3,362.

FARADAY'S ELECTRICAL RESEARCHES.

There seems little doubt that the start of this great work was the construction, when a poor bookbinder's apprentice in 1812, of a voltaic pile with 7 halfpence, 7 discs of sheet zinc and 6 pieces of paper moistened with salt water, with which Faraday decomposed sulfate of magnesia as described in a letter to his friend Abbott on July 12, 1812.

It was only after a vast amount of chemical work which embraced important discoveries—the liquefaction of chlorine, the isolation of benzene, the preparation of alloy steels and special glasses—that Faraday started his electrical researches. He was impressed with the relation of magnetism to electricity and, stimulated by the idea of the convertibility of the different forms of energy which ran persistently through his work, he tried again and again to generate an electric current from permanent and electro-magnets. In 1821 and again in 1824, 1825 and 1828 we find him persevering in this search. It was not until August 29, 1831, that he was first able to detect induced currents and after 10 days of intensive work he gave the world his crowning discovery of electromagnetic induction.[5]

Excited and stimulated by this work, Faraday dedicated his life to further electrical research. In 1832 he carried out a methodical study of the "Identity of the Electricities." Although the work of Wollaston and others had left little doubt that frictional electricity ("Franklinic" or "common" as Faraday called it) and voltaic electricity only varied in the quantity and intensity in which they generally appeared,[6] the proofs were not precise enough to settle the question or satisfy the high standard which Faraday himself demanded. This particular investigation is of interest to us as it embodies a great deal of important electrochemical study. Measurements were made of electrolysis by electric currents from diverse sources, the strength of the currents were measured by the deflections of an astatic galvanometer, the electrochemical decomposition being noted on a variety of materials. Finally Faraday convinced himself that electricity from the most diverse sources was identical and published the following table to summarise his conclusions.

[5] The Faraday Centenary Celebrations held in London in 1931 were dated to commemorate this event whilst embracing his other discoveries. The exhibition of historical apparatus and the sections illustrating the modern developments which have followed from his work, formed an important part of these celebrations.

[6] J. G. Children, Phil. Trans. Royal Soc., 1815, p. 363, describes the construction and use of a large battery with plates 6 ft. x 2 ft. 8 in. (183 x 81 cm.), hoping that on this larger scale the voltaic cell would give more powerful effects.

*Table of the Experimental Effects Common to the Electricities Derived from Different Sources.*

| | Physiological Effects | Magnetic Deflection | Magnets made | Spark | Heating Power | The Chemical Action | Attraction and Repulsion | Discharge by Hot Air |
|---|---|---|---|---|---|---|---|---|
| 1. Voltaic electricity.. | X | X | X | X | X | X | X | X |
| 2. Common electricity.. | X | X | X | X | X | X | X | X |
| 3. Magneto-electricity.. | X | X | X | X | X | X | X | .. |
| 4. Thermo-electricity.. | X | X | + | + | + | + | .. | .. |
| 5. Animal electricity.. | X | X | X | + | + | X | .. | .. |

It is interesting to note some of the apparatus which Faraday used. His voltaic battery, evidently of the Wollaston type, consisted of 10 pairs of plates 4 in. (10 cm.) square, double coppers and a central zinc to each pair. The electrical machine was of the plate type, 50 in. (127 cm.) in diameter and was used with 15 large Leyden jars. The galvanometers were astatic with two coils of copper wire.

Attention is drawn by Faraday to the very small electrolytic decomposition by frictional electricity and particularly by atmospheric electricity, compared with that from the voltaic pile. In 1833 Faraday again refers to the unbelievably small electric current in a thunder storm and concludes that the electricity in a single grain of water is "equal in quantity to that in a powerful thunder storm."[7]

During the year 1833 and the first half of January, 1834, Faraday was mainly occupied with the study of electrolytic decomposition and, as usual, planned and varied his experiments widely to test and demonstrate the prolific ideas which were passing through his mind. Some quotations from the Diary and from the 7th series of his "Experimental Researches in Electricity" will perhaps best reveal the outstanding points and illustrate his method of working and the results achieved.

[7] Modern research by C. T. R. Wilson indicates that in a lightning flash the quantity of electricity varies between 10 and 50 coulombs, 20 coulombs being typical; whereas the potential is of the order of a thousand million volts, and the energy dissipated in an average lightning discharge is of the order of 3,000 kilowatt hours. See G. C. Simpson, Kelvin Lecture, Institution of Electrical Engineers (London), **7**, 1275-6 (1929).

EXTRACTS FROM DIARY.

February 15, 1833.

287. "Does it not shew very important relation between the decomposability of such bodies and their conducting power, as if here the electricity were only a transfer of a series of alternations or vibrations and *not* a body transmitted directly. May settle or relate to question of materiality or fluid of Electricity."

February 18, 1833.

300. "*Chloride of Silver*—most beautiful—fuzed by lamp on glass—conducts well—intense action—deep descoloration at P. Pole and apparently chloride platina formed. Metallic silver at N. Pole and on lifting up pole drew out a wire of silver, the metal being reduced as it went on and the communication being completed through it. Might in this way draw out silver bar at rate of ½ inch per second quite regular."

May 16, 1833.

521. "Is the law this (above a certain intensity, i.e., the one required for decomposition to take place at all), that whatever the size of plates or number intervening, or constant section of decomposing matter, or variable section or variable length or variable strength or number of series in the battery; that (provided other decompositions do not mask the indicating one) equal currents of electricity measured by the galvanometer evolve equal volumes of gas or effect equal chemical action in a constant medium?"

September 20, 1833.

745. "As to peculiar effects of the P. and N. Pole, will Pos. pole act as less oxidable metal to a piece of platina in common state? If so will N. Pole act as more oxidable metal to Do.? If so then both poles in peculiar state, but opposite to each other, and may consider that whilst P. Pole has power of combination when alone, N. Pole has probably power of decomposition or something equivalent to it. Extend this view by thought and experiment."

September 21, 1833.

760. "Have constructed a new decomposing tube intended to be a volta-electrometer.[8] It is about [8] inches long and [0.7] of an inch in diameter. Two platina wires soldered to plate platina poles passed through the side, being hermetically sealed there. So that the tube can be filled with dilute acid or any other solution, inverted in a cup of the same solution: the poles can be connected with the battery, or with other apparatus, and the gas evolved can be collected above out of contact with the Pos. or Neg. pole. No after action of absorption or condensation was found to occur here. Will for the future call this tube A."

September 23, 1833.

801. "Think it will be very important to have a new relation of bodies under the term *electrochemical equivalents*—tabulated. Very important as to decomposing powers of the pile—as to the true expression of equivalent numbers and as to nature of chemical affinity and its relation to electrical states and powers."

December 17, 1833.

1171. "Proceeded to decompose dry chlorides, oxides, etc., etc., to ascertain if there also the decomposition was definite and what the equivalent numbers would be."

[8] Later this word was contracted to "Voltameter" as used today for such instruments.

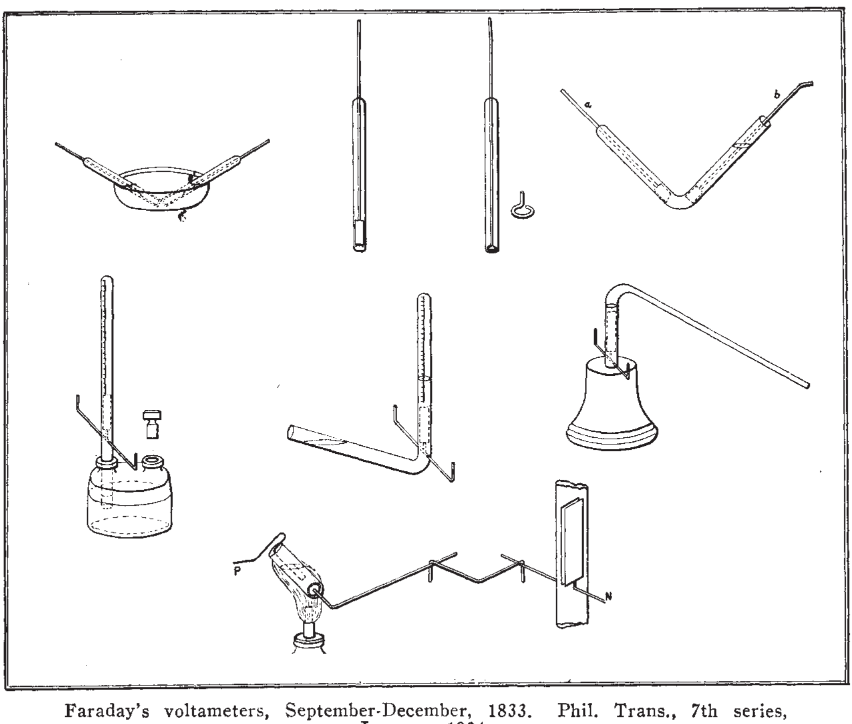
1176. "The number for Tin is given 58, which is very near indeed for a first expt., and shews that the Electrochem. equivalent is the same as the Chemical equivalent here. The excess of tin above 58 is probably due to the deficiency of gas in the Volta Electrometer from absorption, etc., etc."

1177. "It is probable that a better volta electrometer would be to act on a chloride, as lead or tin, etc., and estimate the electricity by the weight of the latter. Or even humid solutions might be employed; thus the lead or Tin or copper thrown down from a solution would, if washed, dried and weighed, do as well as the volume of gas and be free from the objection of absorption *for probably all these precipitates are electrochemical equivalents* in their purest condition. Then indeed have an admirable means of comparing numbers of definite proportionals, etc., etc., etc."

December 19, 1833.

1207. "In the table I mean Real Electro chemical equivalents, not hypothetical; for we shall else outrun fact and lose the information directly before us. It does not follow that all bodies which combine should be in the combining proportions. Electrochemical equivalents: I must keep my researches really *Experimental* and not let them deserve any where the character of *hypothetical imaginations.*"

1213. "This process may finally give rise to some very good processes of analysis in determining weights, or at least to some excellent modes of comparing weights of metals. Thus by submitting vessels containing Chlorides of lead, tin, etc., etc., to same current, get the comparative quantities very accurately *a good principle of analysis,* for it will hold probably in salts as well if properly selected, and may use mercury electrodes when convenient."




Faraday's voltameters, September-December, 1833. Phil. Trans., 7th series, January, 1834.

December 26, 1833.

1273. "It is wonderful to observe how small a quantity of a compound body, water for instance, is decomposed by a certain portion of Electricity. *One grain* for instance by a powerful current continued for some time. Yet here the relation of conduction and decomposition so close that (it) is probably a true result and the only kind of true result as yet supplied by expt., and it is most likely true that if all the Electricity which acts when the Elements of a grain of water unite could be brought into an available current, it would equal the current required for its decomposition. *Enormous.*"

EXTRACTS FROM FARADAY'S EXPERIMENTAL RESEARCHES IN ELECTRICITY.
(PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY)

5th Series June, 1833.

505. "I have still reason to believe that the statement might be made still more general, and expressed thus: That for a *constant quantity of electricity, whatever the decomposing conductor may be, whether water, saline solutions, acids fused bodies, etc., the amount of electrochemical action is also a constant quantity, i.e., would always be equivalent to a standard chemical effect founded upon ordinary chemical affinity.* I have this investigation in hand, with several others, and shall be prepared to give it in the next series but one of these Researches."

518. "Passing to the consideration of electrochemical decomposition, it appears to me that the effect is produced by an *internal corpuscular action,* exerted according to the direction of the electric current, and that it is due to a force either *super-added to,* or *giving direction to the ordinary chemical affinity* of the bodies present. The body under decomposition may be considered as a mass of acting particles, all those which are included in the course of the electric current contributing to the final effect; and it is because the ordinary chemical affinity is relieved, weakened, or partly neutralized by the influence of the electric current in one direction parallel the course of the latter, and strengthened or added to in the opposite direction, that the combining particles have a tendency to pass in opposite courses.

524. "I hope I have now distinctly stated, although in general terms, the view I entertain of the cause of electrochemical decomposition, *as far as that cause can at present be traced and understood.* I conceive the effects to arise from forces which are *internal,* relative to the matter under decomposition—and not *external,* as they might be considered, if directly dependent upon the poles. I suppose that the effects are due to modification, by the electric current, of the chemical affinity of the particles through or by which that current is passing, giving them the power of acting more forcibly in one direction than in another, and consequently making them travel by a series of successive decompositions and recompositions in opposite directions, and finally causing their expulsion or exclusion at the boundaries of the body under decomposition, in the direction of the current, *and that* in larger or smaller quantities, according as the current is more or less powerful" (377).

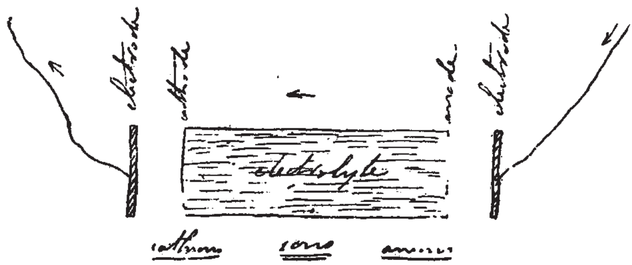
7th Series. January, 1834.

732. "I consider the foregoing investigation as sufficient to prove the very extraordinary and important principle with respect to WATER, *that when subjected to the influence of the electric current, a quantity of it is decomposed exactly proportionate to the quantity of electricity which has passed,* not withstanding the thousand variations in the conditions and circumstances under which it may at the time be placed; and further, that when the interference of certain secondary effects (742, etc.) together

with the solution or recombination of the gas and the evolution of air, are guarded against, *the products of the decomposition may be collected with such accuracy, as to afford a very excellent and valuable measurer of the electricity concerned in their evolution.*"

821. "All these facts combine into, I think, an irresistible mass of evidence, proving the truth of the important proposition which I at first laid down, namely, *that the chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes* (377.783). They prove, too, that this is not merely true with one substance, as water, but generally with all electrolytic bodies; and, further, that the results obtained with any *one substance* do not merely agree amongst themselves but also with those obtained from *other substances,* the whole combining together into *one series of definite electrochemical actions* (505) . . . . . . . . .

824. "Then, again, the substances into which these divide, under the influence of the electric current, form an exceedingly important general class. They are combining bodies; are directly associated with the fundamental parts of the doctrine of chemical affinity and have each a definite proportion, in which they are always evolved during electrolytic action. I have proposed to call these bodies generally *ions,* or particularly *anions* and *cations,* according as they appear at the *anode* or *cathode* (665.); and the number representing the proportions in which they are evolved *electrochemical equivalents.* Thus hydrogen, oxygen, chlorine, iodine, lead, tin, are *ions;* the three former are *anions,* the two metals are *cations,* and 1, 8, 36, 125, 104, 58 are their *electrochemical equivalents* nearly[9]."




Faraday's nomenclature of electrolysis, 1834. Original sketch by Faraday to illustrate his new terms.

845. "I give the following brief Table of *ions* and their electrochemical equivalents, rather as a specimen of a first attempt than, as anything that can supply the want which must very quickly be felt, of a full and complete tabular account of this class of bodies. Looking forward to such a table as of extreme utility (if well constructed) in developing the intimate relation of ordinary chemical affinity to electrical actions, and identifying the two, not to the imagination merely but to the conviction of the senses and a sound judgement, I may be allowed to express a hope, that the endeavour will always be to make it a table of *real,* and not *hypothetical,* electrochemical equivalents; for we shall else overrun the facts, and lose all sight and consciousness of the knowledge lying directly in our path."

[9] As an illustration of Faraday's keen desire to avoid all terms tainted by a foregone conclusion, reference should be made to his correspondence with W. Whewell of Trinity College, Cambridge, in May, 1834. It was Whewell who suggested these terms after carefully considering the exact meaning Faraday wished to convey. This new nomenclature undoubtedly clarified the whole science of electrochemistry and the terms are in universal use today. A reproduction is given of the sketch by Faraday made in his own copy of the reprints of his Phil. Trans. Paper to illustrate these terms.

846. "The equivalent numbers do not profess to be exact, and are taken almost entirely from the chemical results of other philosophers in whom I could repose more confidence, as to these points than in myself."

847. TABLE OF IONS.

*Anions.*

| | | | | | |
|---|---|---|---|---|---|
| Oxygen | 8 | Selenic acid | 64 | Tartaric acid | 66 |
| Chlorine | 35.5 | Nitric acid | 54 | Citric acid | 58 |
| Iodine | 126 | Chloric acid | 75.5 | Oxalic acid | 36 |
| Bromine | 78.3 | Phosphoric acid | 35.7 | Sulphur (?) | 16 |
| Fluorine | 18.7 | Carbonic acid | 22 | Selenium (?) | |
| Cyanogen | 26 | Boracic acid | 24 | Sulpho-cyanogen | ... |
| Sulphuric acid | 40 | Acetic acid | 51 | | |

*Cations.*

| | | | | | |
|---|---|---|---|---|---|
| Hydrogen | 1 | Cadmium | 55.8 | Soda | 31.3 |
| Potassium | 39.2 | Cerium | 46 | Lithia | 18 |
| Sodium | 23.3 | Cobalt | 29.5 | Baryta | 76.7 |
| Lithium | 10 | Nickel | 29.5 | Strontia | 51.8 |
| Barium | 68.7 | Antimony | (?)64.6 | Lime | 28.5 |
| Strontium | 43.8 | Bismuth | 71 | Magnesia | 20.7 |
| Calcium | 20.5 | Mercury | 200 | Alumina | (?) |
| Magnesium | 12.7 | Silver | 108 | Protoxides generally | |
| Manganese | 27.7 | Platina | (?)98.6 | Quinia | 171.6 |
| Zinc | 32.5 | Gold | (?) | Cinchona | 160 |
| Tin | 57.9 | ............... | | Morphia | 290 |
| Lead | 103.5 | Ammonia | 17 | Vegeto-alkalies generally | |
| Iron | 28 | Potassa | 47.2 | | |
| Copper | 31.6 | | | | |

861. "What an enormous quantity of electricity, therefore, is required for the decomposition of a single grain of water! We have already seen that it must be in quantity sufficient to sustain a platina wire 1/104 of an inch in thickness, red hot, in contact with the air, for three minutes and three quarters (853.), a quantity which is almost infinitely greater than that which could be evolved by the little standard voltaic arrangement to which I have just referred (860. 371). I have endeavoured to make a comparison by the loss of weight of such a wire in a given time in such an acid, according to a principle and experiment to be almost immediately described (862.) but the proportion is so high that I am almost afraid to mention it. It would appear that 800,000 such charges of the Leyden battery as I have referred to above, would be necessary to supply electricity sufficient to decompose a single grain of water; or if I am right, to equal the quantity of electricity which is naturally associated with the elements of that grain of water, endowing them with their mutual chemical affinity."

In this short space of time by January, 1834, Faraday had laid the foundations of theoretical and applied electrochemistry. The 7th Series of his Experimental Researches published in January, 1834, represents his most important contribution to electrochemistry, as can be seen by briefly summarising the results.

1. A nomenclature for the phenomena of electrolysis is provided which itself greatly clarified their understanding.

2. The fundamental ideas of the mechanism of electrolysis were improved; it being shown that conduction and decomposition were not due merely to the attractions of the poles or electrodes but were mainly associated with "the internal corpuscular actions" associated with the interrelation of electricity and chemical affinity.

3. The First Law of Electrolysis was established **"that the chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes."**

4. The Second Law of Electrolysis was also formulated **that "electrochemical equivalents coincide, and are the same, with ordinary chemical equivalents."**

In establishing these laws Faraday exhibited his extraordinary genius in utilising experimental work with proper interpretation of its quantitative results. He duly noted the great complications caused by secondary reactions at the electrodes; and by their detailed study was able to understand to what degree they affected in some cases his simple laws. Without such genius the validity of these laws might for long have been hidden from us.

Faraday's next electrochemical research was a study, "the great question of the source of electricity in the voltaic pile," a subject which long before and for long after engaged the attention of leading scientists.[10] The theory that by the contact of the metals electricity was produced never satisfied him and, although it was before the enunciation of the laws of Conservation of Energy by Joule in 1843, Faraday clearly shows that he grasped the important facts and was firmly convinced of the quantitative relationship of the different forms of energy. The 8th Series of his Electrical Researches gives an account of his extensive experimental work on the voltaic pile and the new electrochemical ideas which arose from these experiments. The close inter-relationship of the chemical and electrical phenomena are further clarified and emphasised, as for instance in the following quotations:

FARADAY'S EXPERIMENTAL RESEARCHES IN ELECTRICITY.
SERIES VIII. APRIL, 1834

917. "As *volta-electro-generaton* is a case of mere chemical action, so volta-electro-decomposition is simply a case of the preponderance of one set of chemical affinities more powerful in their nature, over another set which are less powerful: and if the instance of two opposing sets of such forces (891.) be considered, and their mutual relation and dependence borne in mind, there appears no necessity for using, in respect to such cases, any other term than chemical affinity (though that of electricity may be very convenient), or supposing any new agent to be concerned in producing the results; for we may consider that the powers at the two places of action

[10] See Oliver Lodge *loc. cit.*

are in direct communion and balanced against each other through the medium of the metals (891), fig. 76, in a manner analogous to that in which mechanical forces are balanced against each other by the intervention of the lever (1031.)."

918. "All the facts show us that that power commonly called chemical affinity, can be communicated to a distance through the metals and certain forms of carbon; that the electric current is only another form of the forces of chemical affinity; that its power is in proportion to the chemical affinities producing it; that when it is deficient in force it may be helped by calling in chemical aid, the want in the former being made up by an equivalent of latter; that, in other words, *the forces termed chemical affinity and electricity are one and the same.*"

Despite the strong case for the chemical action being the source of the electricity in the voltaic pile, the contact theory was still strongly supported. Faraday returned to this subject and in the 17th Series of the Electrical Researches published in January, 1840, he publishes a large amount of further experimental evidence in favour of the chemical theory. This paper is of great historic importance since it exposes clearly how near Faraday was to the law of Conservation of Energy put forward by Joule in 1843. The quotation is worth giving.

FARADAY'S EXPERIMENTAL RESEARCHES IN ELECTRICITY.
SERIES XVII. JANUARY, 1840.

2071. "The contact theory assumes, in fact, that a force which is able to overcome powerful resistance, as for instance that of the conductors, good or bad, through which the current passes, and that again of the electrolytic action where bodies are decomposed by it, can arise out of nothing; that, without any change in the acting matter or the consumption of any generating force, a current can be produced which shall go on for ever against a constant resistance, or only be stopped, as in the voltaic trough by the ruins which its exertion has heaped up in its own course. This would indeed be *a creation of power,* and is like no other force in nature. We have many processes by which the form of the power may be so changed that an apparent conversion of one into another takes place. So we can change chemical force into the electric current, or the current into chemical force. The beautiful experiments of Seebeck and Peltier show the convertibility of heat and electricity; and others by Oersted and myself show the convertibility of electricity and magnetism. But in no cases, not even those of the Gymnotus and Torpedo (1790.), is there a pure creation of force; a production of power without a corresponding exhaustion of something to supply it."

2072. "It should ever be remembered that the chemical theory sets out with a power the existence of which is pre-proved, and then follows its variations rarely assuming anything which is not supported by some corresponding simple chemical fact. The contact theory sets out with an assumption, to which it adds others as the cases require, until at last the contact force, instead of being the firm unchangeable thing at first supposed by Volta, is as variable as chemical force itself."

2073. "Were it otherwise than it is, and were the contact theory true, then, as it appears to me, the equality of cause and effect must be denied (2069). Then would the perpetual motion also be true; and it would not be at all difficult, upon the first given case of an electric current by contact alone, to produce an electro-magnetic arrangement, which as to its principle, would go on producing mechanical effects for ever."

In carrying out this experimental work on voltaic cells Faraday turned his attention to the improvement of the voltaic battery. The early forms of voltaic battery available to Davy and Faraday at the Royal Institution were somewhat primitive and rapidly became exhausted. The intensity of these batteries was, however, rather remarkable. For instance, in 1808, by the subscription of its members, the Royal Institution was provided with a battery of 2,000 double plates of copper and zinc with a total surface of 128,000 sq. in. (825,600 $cm.^2$). Later the life of the battery was greatly extended by the simple device introduced by Wollaston for lifting the plates out of the acid when not in use. Faraday described a further great improvement introduced by Dr. Robert Hare, M.D., Professor of Chemistry of Philadelphia University[11] in which double troughs at right angles to one another were used, enabling the battery to be tilted for pouring on or off the acid. None of these voltaic batteries, however, were really satisfactory or capable of providing a sustained steady current.

A great practical advance was made in 1836 by Professor J. F. Daniell, a disciple of Faraday, who described the first "Constant Battery" which is still a type in use today and which from that time until about 1866, when dynamos were first generally used, was employed in the industrial applications of electrochemistry and electrometallurgy.

One further important step which led to the rapid advance of electrolytic processes was the discovery in 1838 by Prof. Jacobi of St. Petersburg of copper electrotyping for making facsimile reproductions of engravings or formed surfaces. This was followed by the inventions of Elkington for electrogilding in 1838 and for silver plating in 1840. How rapid was the interest taken in electrometallurgy from this time is clearly brought out in the book published by Alfred Smee, F.R.S., Surgeon to the Bank of England, the first edition of which appeared in December, 1840, in which he says "There is not a town in England that I have happened to visit, and scarcely a street of this metropolis, where prepared plasters are not exposed to view for the purpose of alluring persons to follow the delightful recreation afforded by the practice of electrometallurgy." This is not the place to attempt the assessment of the modern developments which have directly arisen from the epoch-making work of Faraday. This whole electrical age depends upon the generation of currents by methods based on the principle of electromagnetic induction which he first unrolled. In electrochemical industry the recent review for our Society by Mr.

[11] American Journal of Science, 7, 347-351 (1824).

C. L. Mantell[12] gives some indication of the vast amount of electric current which is utilised industrially.

As we have seen, one of the main guiding impulses of Faraday's work was the inter-relation of the 'forces' or forms of energy and he was constantly thinking and working on the transformation of one of these into another. Magnetism, electricity, chemical action, gravitation and later light occupied his mind and formed the basis of extensive experimental studies. From all this scientific work practical results of vast importance arose.

Faraday himself was wide awake and keenly interested in the practical applications of science but with the rare spirit of the true philosopher restrained himself from spending his own time on the larger scale development of his results. For instance, in connection with his magnetic electrical machines he records: "I have rather, however, been desirous of discovering new facts and new relations dependent on magneto-electric induction than of exalting the force of those already obtained; being assured that the latter would find their full development hereafter."

## EPILOGUE.

Reference was made to the foundation of the Royal Institution in 1800, the prime mover being an American, Benjamin Thompson (Count Rumford).

We have seen how Faraday's loyalty and splendid work kept the Royal Institution from dissolution at the critical period of its career.

Faraday held his Fullerian Professorship of chemistry from its foundation in 1833 until 1867. His successors have been the following: 1868-1873, William Odling; 1874-1877, J. H. Gladstone; 1877-1923, Sir James Dewar; and since 1923 Sir William Bragg. All these men have maintained the traditional spirit of the Royal Institution as the home of fundamental scientific research and the platform for scientific lectures both to expert and lay audiences.

The foundation of the Davy-Faraday Research Laboratory as an annex to the Royal Institution by the late Dr. Ludwig Mond and the recent reconstruction of the famous lecture theatre with important structural alterations have fully maintained the first-class character of the Royal Institution.

Recently a special Building and Research Endowment Fund was collected, attaining almost $500,000 to which substantial contributions

[12] Trans. Electrochem. Soc., 62, 15 (1932).

were made by the Pilgrims' Trust and the Rockefeller Foundation, thus maintaining the American interest in this famous Institution and its work.

## APPENDIX.

### SOME FARADAY MAXIMS.

As throwing further light on the character of Faraday the following selected quotations from his writings are collected from diverse sources:

1. "Let me, as an old man who ought by this time to have profited by experience, say that when I was younger I found I often misinterpreted the intentions of people, and found they did not mean what at the time I supposed they meant; and further, that as a general rule, it was better to be a little dull of apprehension when phrases seemed to imply pique, and quick in perception when, on the contrary, they seemed to imply kindly feeling. The real truth never fails ultimately to appear; and opposing parties, if wrong, are sooner convinced when replied to forbearingly than when overwhelmed."

Secret of success as a scientific worker:

2. "The secret is compounded in three words—Work, Finish, Publish."

3. "The Philosopher should be a man willing to listen to every suggestion but determined to judge for himself. He should not be biassed by appearances, have no favourite hypothesis, be of no school, and in doctrine have no master. He should not be a respecter of person, but of things. Truth should be his primary object. If to these qualities be added industry, he may indeed hope to walk within the veil of the temple of Nature."

4. "He is the wisest philosopher who holds his theory with some doubt—who is able to proportion his judgment and confidence to the value of the evidence set before him, taking a fact for a fact and a supposition for a supposition, as much as possible keeping his mind free from all source of prejudice, or where he cannot do this (as in the case of a theory), remembering that such a source is there."

5. "Remember to do one thing at once. Also to finish a thing. Also to do a little if I could not do *much.*"

6. "Aim at high things, but not presumptuously. Endeavour to succeed—expect not to succeed. *Criticise* one's own view in every way by experiment—if possible leave no objection to be put by others."

7. THE FOUR DEGREES.

The discoverer of a fact.
The reconciling of it to known principles.
Discovery of a fact not reconcilable.
He who refers all to still more general principles.

8. "As an experimentalist, I feel bound to let experiment guide me into any train of thought which it may justify; being satisfied that experiment, like analysis, must lead to strict truth if rightly interpreted; and believing also that it is in its nature far more suggestive of new trains of thought and new conditions of natural power."

9. "I cannot but doubt that he who as a mere philosopher has most power of penetrating the secrets of nature, *and guessing* by hypothesis at her mode of working, will also be most careful for his own safe progress and that of others to distinguish the knowledge which consists of assumption, by which I mean theory and hypothesis, from that which is the knowledge of facts and laws."

10. "I was never able to make a fact my own without seeing it; and the description of the best works altogether failed to convey to my mind such a knowledge of things as to allow myself to form a judgment upon them. It was so with *new* things. If Grove, or Wheatstone, or Gassiot, or any other told me a new fact, and wanted my opinion either of its value or the cause or the evidence it could give on any subject, I never could say anything until I had seen the fact. For the same reason I never could work, as some Professors do most extensively, by students or pupils. All the work had to be my own."

A preface to one of Faraday's Note Books reads as follows:

"CHEMICAL NOTES, HINTS, SUGGESTIONS, AND OBJECTS OF PURSUIT"

11. "I already owe much to these notes and think such a collection worth the making by every scientific man. I am sure none would think the trouble lost after a year's experience. M. F. 1822."

12. "Let the imagination go guiding it by judgment and principle but holding it in and directing it by experiment."

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